

Review

Bioremediation Treatment of Polyaromatic Hydrocarbons for Environmental Sustainability

Marjan Salari ¹, Vahid Rahmanian ², Seyyed Alireza Hashemi ³, Wei-Hung Chiang ⁴, Chin Wei Lai ⁵, Seyyed Mojtaba Mousavi ^{4,*} and Ahmad Gholami ^{6,*}

- ¹ Department of Civil Engineering, Sirjan University of Technology, Sirjan P.O. Box 7813733385, Iran
² The Centre of Molecular and Macromolecular Studies, Polish Academy of Sciences, Sienkiewicza 112, 90-363 Lodz, Poland
³ Nanomaterials and Polymer Nanocomposites Laboratory, School of Engineering, University of British Columbia, Kelowna, BC V1V 1V7, Canada
⁴ Department of Chemical Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan
⁵ Nanotechnology and Catalysis Research Centre (NANOCAT), Institute for Advanced Studies (IAS), University of Malaya (UM), Kuala Lumpur 50603, Malaysia
⁶ Biotechnology Research Center, Department of Pharmaceutical Biotechnology, Faculty of Pharmacy, Shiraz University of Medical Science, Shiraz 71345-1583, Iran
* Correspondence: kempo.smm@gmail.com (S.M.M.); gholami@sums.ac.ir (A.G.)

Abstract: Polycyclic aromatic hydrocarbons (PAHs) distributed in air and soil are harmful because of their carcinogenicity, mutagenicity, and teratogenicity. Biodegradation is an environmentally friendly and economical approach to control these types of contaminants and has become an essential method for remediating environments contaminated with petroleum hydrocarbons. The bacteria are isolated and identified using a mineral nutrient medium containing PAHs as the sole source of carbon and energy and biochemical differential tests. Thus, this study focuses on some bacteria and fungi that degrade oil and hydrocarbons. This study provides a comprehensive, up-to-date, and efficient overview of petroleum hydrocarbon contaminant bioremediation considering hydrocarbon modification by microorganisms, emphasizing the new knowledge gained in recent years. The study shows that petroleum hydrocarbon contaminants are acceptably biodegradable by some microorganisms, and their removal by this method is cost-effective. Moreover, microbial biodegradation of petroleum hydrocarbon contaminants utilizes the enzymatic catalytic activities of microorganisms and increases the degradation of pollutants several times compared to conventional methods. Biological treatment is carried out in two ways: microbial stimulation and microbial propagation. In the first method, the growth of indigenous microorganisms in the area increases, and the pollution is eliminated. In the second method, on the other hand, there are no effective microorganisms in the area, so these microorganisms are added to the environment.

Keywords: enzymatic treatment; polycyclic aromatic hydrocarbons (PAHs); bioremediation; environmental; sustainability



Citation: Salari, M.; Rahmanian, V.; Hashemi, S.A.; Chiang, W.-H.; Lai, C.W.; Mousavi, S.M.; Gholami, A. Bioremediation Treatment of Polyaromatic Hydrocarbons for Environmental Sustainability. *Water* **2022**, *14*, 3980. <https://doi.org/10.3390/w14233980>

Academic Editor: Chao Yang

Received: 21 October 2022

Accepted: 1 December 2022

Published: 6 December 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The polycyclic aromatic hydrocarbon (PAH) group includes a wide range of compounds with anything from two to seven benzene rings. When organic molecules such as those found in fossil fuels are burned incompletely, they release a wide variety of pollutants known as polycyclic aromatic hydrocarbons (PAHs) [1]. Some PAHs are dangerous to human health because they cause cancer, genetic mutations, and congenital disabilities. Therefore, the potential for PAHs to disperse farther in nature is raised [2]. PAHs (polychlorinated biphenyls) enter the environment via natural and human activities. PAHs are ubiquitous because they are produced during the combustion of almost all organic

materials. Incomplete combustion of fuels, trash, or other organic matter (including tobacco and plant material) are all potential sources of PAHs and their derivatives [3].

Natural sources of PAHs include, but are not limited to, forest fires, volcanic eruptions, and animal feces. Given that aromatic compounds are created from petroleum and petroleum products, it is vital to address the petroleum, petrochemical, and processing sectors and the pollution they generate [4]. Crude oil, which can be refined into more than 340 different products, is one of the essential energy sources and the engine of the global economy. Because of fast population expansion and energy use, oil contamination is practically unavoidable. Transportation and storage may taint petroleum fuels and their derivatives. The greater the penetration depth of petroleum products into the soil, the more difficult it is to remove the pollutants [5]. Certain bacteria and microorganisms in the soil may decompose petroleum compounds [6,7]. When it comes to cleaning up polluted areas, bioremediation is a top priority. In this process, biological organisms, primarily bacteria, fungi, and plants, degrade environmental contaminants and transform them into harmless chemicals [8,9]. These microbes convert hydrocarbon molecules into carbon dioxide, biomass, or other products. The effectiveness and pace of hydrocarbon degradation rely on the kind of pollutants, the composition of the contaminated material, the ambient conditions, and the features of the microbial population [10]. Microorganisms may degrade PAH by producing three primary products. (a) Enzymes: monooxygenase and dioxygenase are the essential enzymes for hydrocarbon decomposition, and their result is alcohol [11,12]; (b) biosurfactants: microorganisms create biological materials with hydrophilic and hydrophobic groups on the cell surface. They are classified based on their chemical structure as glycolipids, phospholipids, fatty acids, and lipopolysaccharides. By emulsifying adsorbed hydrocarbons and releasing them into the soil organic matter, biosurfactants enhance the mass transfer rate by raising the water concentration of hydrophobic molecules. They contribute to the acceleration of biodegradation [13]; (c) many bacteria may utilize hydrocarbons as a source of carbon and energy to produce acids and solvents such as acetone, ether, benzene, and oxaloacetic acid, which dissolve petroleum hydrocarbons [14,15]. *Pseudomonas*, *Bacillus*, *Rhodococcus*, *Mycobacterium*, *Acinetobacter*, *Staphylococcus*, *Clostridium*, *Proteus*, and *Micrococcus* are among the most significant bacteria engaged in this process [16–18]. No microorganism alone can completely decompose petroleum hydrocarbons into carbon dioxide and water as the final product. Today, with the help of genetic engineering, several plasmids have been integrated into bacteria, namely *Pseudomonas*, such that they may concurrently break down several petroleum compounds [19]. According to recent research, many nations throughout the globe are confronting a variety of difficulties due to petroleum hydrocarbon pollutants which are themselves persistent organic pollutants. Biodegradation is a viable alternative for cleaning up these polluted locations since traditional physical and chemical approaches are technically and economically challenging [20]. In terms of enhancing life and preserving biodegradable materials in polluted areas, dormant microbial cells are preferable to free microbial cells. However, present techniques for biodegradation are limited by several factors such as the features of the pollutants, the poor capacities of microbial communities, the particular biological presence of a few contaminants, and growing circumstances [21–23]. The routes of hydrocarbon pollutant degradation and diverse bioremediation methods and processes impact the rate of microbial biodegradation, which is the process of microbial transformations of petroleum hydrocarbon pollutants. Considering the consequences of petroleum hydrocarbon pollutants and the scale of those impacts, it is essential to comprehend the elements that influence bioremediation and microbial degradation. This research investigates the bioavailability of substrates, microorganisms in the breakdown of petroleum hydrocarbon pollutants and molecular techniques to characterize them, degradation processes under aerobic and anaerobic circumstances, and variables impacting the biodegradation of these pollutants [24].

2. PAHS Aromatic Hydrocarbons

All compounds with two or more benzene rings fall under this group in a linear, angular, or clustered arrangement. Polycyclic aromatic hydrocarbons are organic chemicals with many rings (Table 1) [25]. This tiny oil fraction is hazardous to plants and animals, but microorganisms can convert PAHs to biomass, carbon dioxide, and water [26,27]. Hydrocarbons with a low molecular weight are poisonous yet swiftly evaporate or disintegrate. In addition, the rate of disintegration of aromatics with several rings is slower than that of those with a single ring. Aromatics with at least five rings are resistant to absorption and may persist in a stable environment [28]. The Food Supply Contaminated With PAHs from many different sources is shown in Figure 1. In Table 1, we have some of the physical and chemical properties of the chosen PAHs [1].

Table 1. Characteristics of physical–chemical priority compounds of PAH contaminants [29,30].

PAH Name	Molecule Formula	Molecular Weight (g/mole)	Aqueous Solubility (mg/L)	Melting Point (°C)	Boiling Point (°C)	Vapor Pressure (Pa, 25 °C)	Log KOW
Naphthalene	C ₁₀ H ₈	128	31.7	80.2	218	11.14	3.30
Acenaphthene	C ₁₂ H ₁₀	154	3.9	90–96	265–280	3.92	3.92
Acenaphthylene	C ₁₂ H ₈	152	16.1	92–93	265–280	3.87	3.94
Fluorene	C ₁₃ H ₁₀	166	1.9	116–118	293–295	1.66	4.18
Phenanthrene	C ₁₄ H ₁₀	178	1.15	96–101	339–340	1.06×10^{-1}	4.46
Pyrene	C ₁₆ H ₁₀	22	0.135	150–156	360–404	5.0×10^{-5}	4.88
Chrysene	C ₁₈ H ₁₂	228	0.002	252–256	441–448	4.0×10^{-6}	5.81
Benzo(2)fluoranthene	C ₂₀ H ₁₂	252	0.0015	198–217	480–471	5.0×10^{-7}	5.78
Benzo(2)fluoranthene	C ₂₀ H ₁₂	252	0.0008	167–168	481	5.2×10^{-8}	6.11
Benzopyrene	C ₂₀ H ₁₂	252	0.00162	177–179	493–496	6.0×10^{-8}	6.13

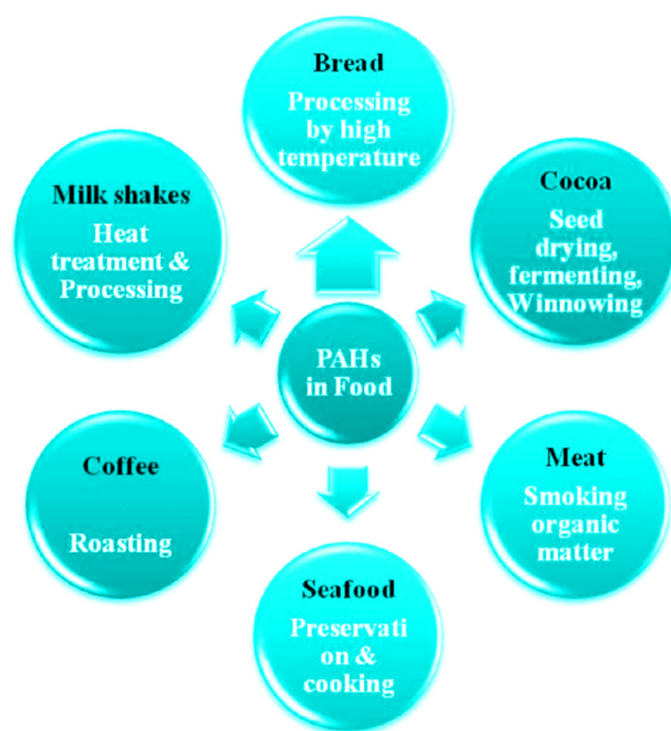


Figure 1. The Food Supply Contaminated With PAHs From many Different Sources (License Number: 5411951000689) [29].

3. The Effects of Oil Pollution on Ecosystems and Human Health

Due to its distinctive chemical features, crude oil is hazardous to human health and ecosystems. Long-term environmental exposure and high quantities cause various cancers and renal and liver problems [31,32]. Aromatic compounds are more harmful than aliphatic compounds, while low molecular weight compounds are more poisonous than those with a considerable molecular weight [33]. The oil component exposed to sunlight is less harmful than its water-soluble counterpart [34]. The PAH contamination in a diverse environment is shown in Figure 2.

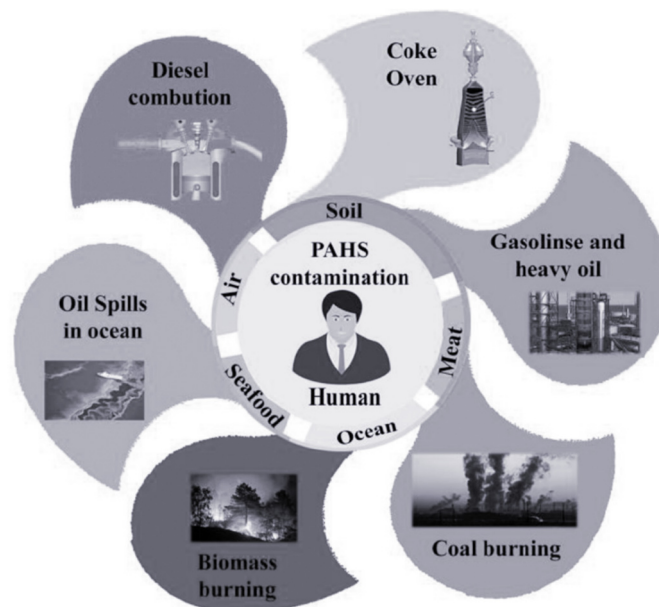


Figure 2. PAH contamination in a diverse environment (License Number: 5411951000689) [29].

Highly toxic polycyclic aromatic hydrocarbons may enter the human body through the skin, respiration, ingestion, and food chain. Breathlessness, a dry cough, chest discomfort, and an irregular pulse are their primary consequences. Additionally, it is very hazardous to marine crustaceans and some aquatic plants and animals, which take it in and store it [35,36].

Oil's impacts on living things are directly proportional to the pollution it causes. As a result, it is essential to conduct systematic research and analysis on pollution to effectively manage polluted ecosystems [34]. The impacts of oil pollution on aquatic ecosystems and associated species extend beyond the levels of primary and secondary producers. Hydrocarbons derived from petroleum affect the semi-permeability of membranes by dissolving lipid molecules, lowering the rate of photosynthesis, and preventing the growth and reproduction of phytoplankton. This phenomenon, which prevents chlorophyll molecules from interacting with one another, is brought on by the breakdown of petroleum hydrocarbons in the lipid phase of chloroplasts. In the mitochondrial membrane, a similar disturbance will hinder the tricarboxylic acid cycle and the oxidative phosphorylation process. While naphthalene lowers the amount of protein in cells, crosne can reroute the lipids found in cell membranes and penetrate harmful red algae.

Additionally, oil disables the feeding route of echinoderms and causes mouth cankers, eye discomfort, and seasickness-related blindness in fish. The oil prevents birds from swimming and flying by penetrating their feathers, replacing water with air, reducing thermal insulation, and decreasing buoyancy. Furthermore, oil toxicity lowers egg viability [37–39].

In mangrove forests, the low oxygen level and high water saturation of sediments inhibit oil breakdown. Aromatic hydrocarbons endure and build for years in these regions; they may stay stable for up to twenty years. In mangrove forests, the floating oil smothers the respiratory and edible roots, resulting in the death of certain trees and the impeded

development of the remaining trees, as seen by leaf loss, fruit degradation, and stunted growth. The loss of their cover demonstrates its impact [40,41].

4. Bioremediation of Petroleum Hydrocarbons

Many common physical and chemical methods are expensive due to the costs of drilling and transporting contaminated materials due to on-site remediation. These methods include soil washing and chemical inactivation (such as using potassium permanganate and hydrogen peroxide) as chemical oxidizers to mineralize insoluble pollutants. Other physical and chemical methods include dispersion, transport, absorption, desorption, and non-living transformation [42]. The high costs and limited effectiveness of these physical and chemical cleaning methods have led to the development of alternative technologies for in situ applications, mainly based on the biological regeneration abilities of plants and microorganisms. General comparison of methods for removing PAHs is shown in Table 2. Biological treatment of oil-contaminated sites using living organisms to destroy and detoxify pollutants can be defined as a green technology, an efficient, economical, and environmentally friendly technique [20]. Removal methods of existing PAHs from the air, soil, and water are shown.

Table 2. General comparison of methods for removing PAHs [20].

Pollutant Removal	An Example of Method	Advantages	Disadvantages
physical	Soil washing	Ease of doing	High cost
Chemical	Chemical inactivation	Affordable	Environmental pollution
Biologically	Bioremediation/microbial degradation	Environment lover	Preparation of microorganism

Pollutant bioremediation is a novel approach to removing hydrocarbon pollutants that involve the transformation of harmful organic pollutants by microorganisms into non-hazardous compounds such as carbon dioxide, methane, water, and biomass. This process does not cause any damage to the surrounding environment. Therefore, biodegradation is one of the most significant methods for eliminating hydrocarbon contaminants from the environment [20,34]. Using microbes is an excellent way to improve the catalytic abilities to live things, which can help get rid of pollutants and improve microbial oil extraction [12,43,44]. Microbial bioremediation of petroleum hydrocarbons is a common way to clean up pollution from petroleum hydrocarbons in terrestrial and aquatic ecosystems. Some microorganisms can break down alkanes or aromatic substances and are more likely to become next-generation hydrocarbon decomposers in polluted areas because they have adapted to the environment and their genes have changed because of petroleum hydrocarbon pollution [45,46]. Due to their propensity to digest hydrocarbon impurities, microorganisms such as bacteria, fungi, and algae are often regarded as the principal decomposers and most active agents in the degradation of petroleum pollutants [7,46]. Biodegradation of pollutants includes successive metabolic processes by enzymes, and the microorganisms for biodegradation are encoded on plasmids for most enzymes [47,48]. Plasmids are necessary to break down hydrocarbons, particularly complex molecules [49,50]. Various enzyme systems can mediate the degradation and decomposition of petroleum hydrocarbons, which are typically the first attack with the mechanisms of (a) binding of microbial cells to the underlying layers and (b) production of biomaterials, biologically active substances or biopolymers, solvents, gases, and acids [51,52]. Organic molecules, such as hydrocarbons, may serve as electron donors for microbial metabolic pathways and, sometimes, as the only carbon source [53]. Oxidation is the initial intracellular defense mechanism against organic contaminants [36]. Oxygenases and peroxidases, which function as oxygen synthesis catalysts, are activated [54]. Environmental degradation mechanisms transform petroleum hydrocarbon contaminants from metabolic to central mediators sequentially. The principal and most expected process for the biodegradation

of these organic pollutants is the biosynthesis of cell biomass from essential precursor metabolites. These metabolites include pyruvate, acetate, and succinate [46,55].

However, many degradation mechanisms and catabolic genes have been discovered for the biodegradation of certain hydrocarbon families. For oxygen to begin and continue the process of biodegradation in the substrate, various enzymes are required. These enzymes depend on the chain length and type of petroleum hydrocarbon pollutants [56,57]. Biological and non-biological processes impacting soil decomposition are shown in Figure 3.

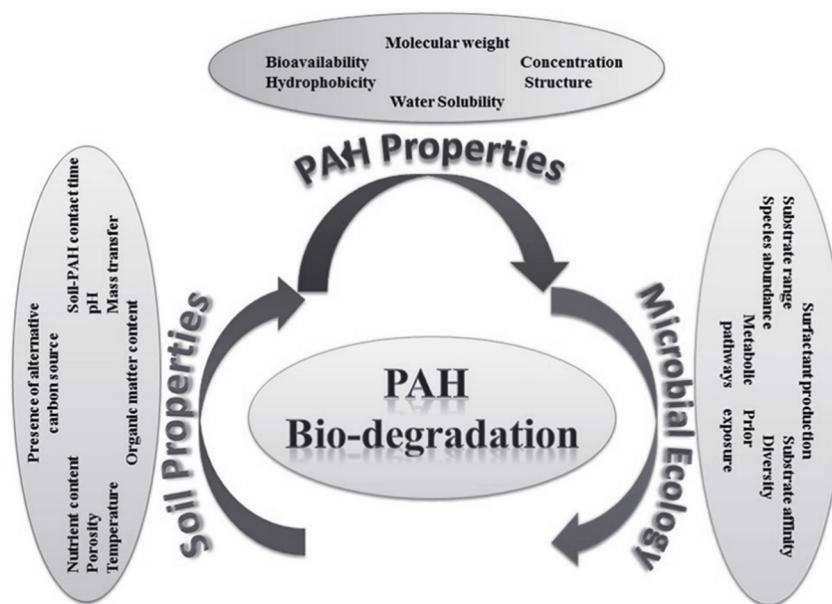


Figure 3. Various variables, both abiotic and biotic, influence the PAH ability to degrade in soil [58].

Metaproteomics and metabolomics have recently been used to explore many facets of environmental microbiology and have shown promise for application in bioremediation. While metabolomics can pinpoint the metabolites created during the biodegradation of PAH, proteomics is a powerful tool for identifying proteins and their participation in PAH breakdown. A summary of the molecular techniques used in the investigation of PAH breakdown by microorganisms is shown in Figure 4. Functional metagenomics, metaproteomics, metabolomics, metatranscriptomics, and DNA microarrays will soon become indispensable tools for understanding the processes that cause PAH biodegradation in the environment. They will also reveal more details about organisms not yet cultured but involved in PAH biodegradation [58].

Genetically Modified Organisms

Bioremediation-capable artificial consortiums or genetically modified organisms may be generated using modern scientific technologies. Using modern molecular biology methods, genetically modified organisms are generated in the laboratory by transferring plasmids carrying the necessary genetic information from external microbes to indigenous microorganisms [59,60]. These genetically engineered microbes can be bioremediate petroleum hydrochloride-contaminated areas [61,62]. Free microorganisms are more tolerant to alkaline and acidic environments and variable NaCl concentrations at low temperatures than the immobilized microbial consortia. It can also degrade 47% more crude oil [63,64]. Regeneration and the disparity between their functional characteristics and stability under laboratory circumstances and the natural environment after environmental treatment are the primary concerns of this cooperation [10,65]. Researchers and industry leaders may investigate immobilizing microbial cells to address pollutants in the oil sector in light of recent developments.

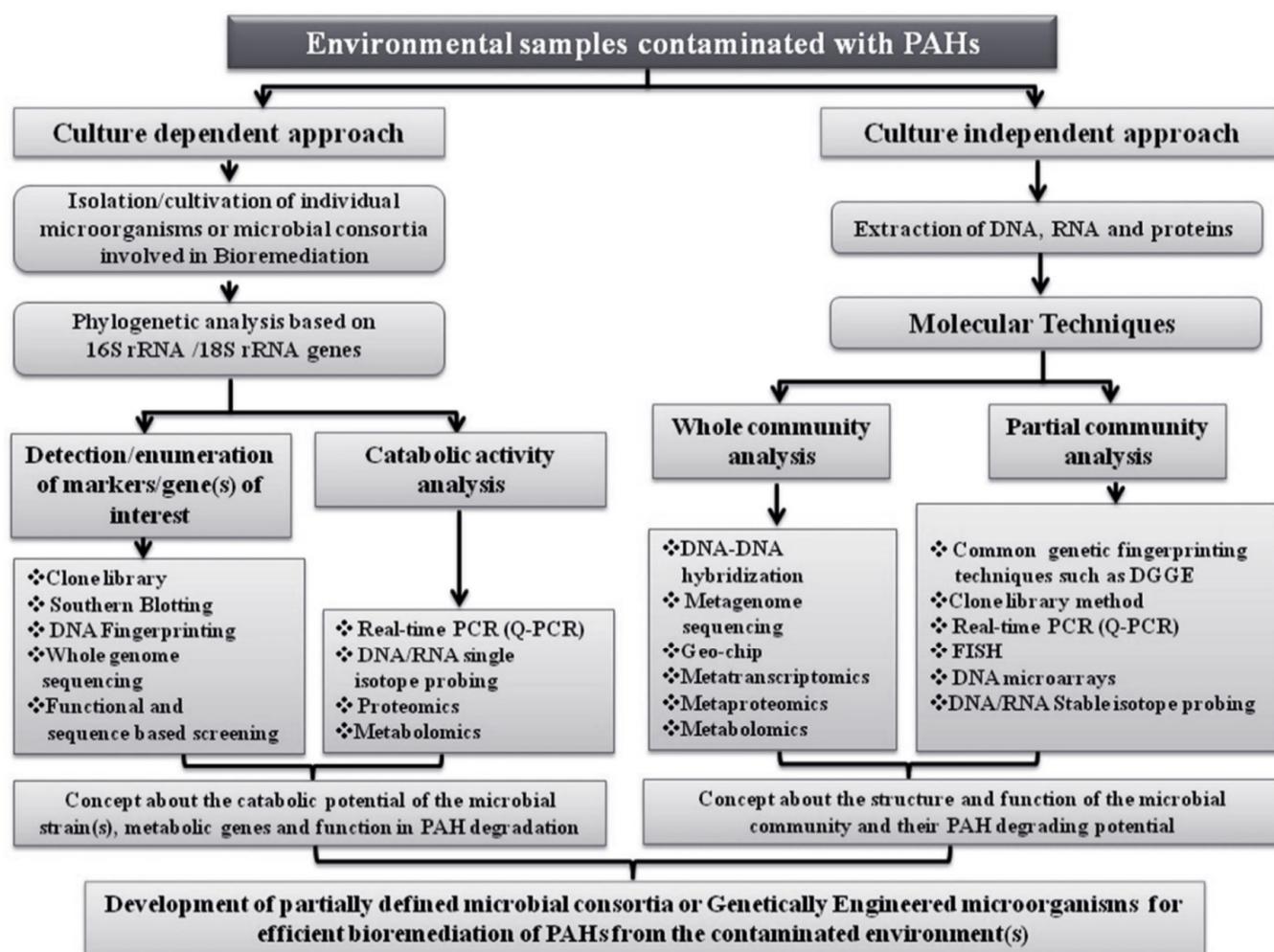


Figure 4. The future path for a better knowledge of microbial PAHs is outlined by a summary of several molecular approaches [58].

5. The Function of Microorganisms

Microorganisms may use petroleum hydrocarbons in phototrophic, hypoxic, chemotrophic, aerobic, and anaerobic modes. The first step of oil pollution affecting microorganisms is the presence of their direct contact with each other. This is a direct link based on the water-repellent properties of the cell wall surface [66,67]. When hydrocarbons come into direct contact with a cell, they enter as minute droplets. Surfactant activity and hydrophobicity then interact with the microbe and the insoluble substrate, circumventing the diffusion constraint in delivering the substrate to the cell. Microbes capable of decomposing oil and the surfactant are more effective for in situ methanogenesis in oil tanks under anoxic circumstances. Microbes that decompose petroleum hydrocarbons create a range of physiologically active compounds, either attached to the cell surface or expelled as extracellular molecules. These chemicals may be found in the environment [68]. Oncological characteristics that promote hydrocarbon bioavailability (microorganism access to substances at the physical and chemical levels), microbial activity, and interaction and transport in microorganisms include the production of a biologically active substance [69]. Bioactive surfactants can efficiently lower the interfacial tension between oil and water and the viscosity of the oil at the site of contamination, as well as destroy up to 77% of the hydrocarbons in crude oil [20,38]. The function of microorganisms on petroleum hydrocarbon pollutants is mediated by enzyme-catalyzed metabolic processes. Significant roles are played by oxygenases, peroxidases, reductases, hydroxylases and dehydrogenases, among

other enzymes. Generally, aerobic and anaerobic routes govern the microbial breakdown of petroleum hydrocarbon pollutants [70].

6. Aerobic Decomposition

Oxidation is the first intracellular assault of organic molecules. Oxygenases and peroxidases are primarily responsible for the activation and combination of oxygen [46,71]. Monooxygenases are enzymes that remove one oxygen atom from the water while simultaneously adding one oxygen atom to the substrate. Low solubility and strong adsorption capability of polyaromatic hydrocarbons often have a considerable impact on biodegradation. Dioxygenases combine oxygen molecules (O₂) into reaction products [72]. The susceptibility of petroleum hydrocarbons to microbial assault varies and is often arranged in declining order: n-alkanes, branched alkanes, aromatics with low molecular weight, and cyclic alkanes [73], i.e., alkyl-cycloalkane side chains accelerate degradation.

Anaerobic Decomposition

Two pathways may lead to the anaerobic degradation of hydrocarbons. The first process combines oxidation components for respiration by reducing an oxygen-free electron receptor (such as sulfate or nitrate), whereas the second pathway involves fermentation [74]. Microorganisms utilize alternate electron receptors such as sulfate, nitrate, iron, manganese, and carbon dioxide in the anaerobic breakdown of petroleum hydrocarbon contaminants [54,75]. However, branched alkanes and most high-molecular-weight polyaromatic hydrocarbons remain a barrier to conversion and degradation for certain hydrocarbon bacteria [74,76]. In prior research, several enzymes decomposed hydrocarbon compounds under aerobic and anaerobic conditions, as shown in Table 3.

Table 3. Bioremediation by microorganisms of polycyclic aromatic hydrocarbons in aerobic and anaerobic environment.

PAHs Used in the Study	Aerobic or Anaerobic Conditions	Microbial Remediation	Degradation Condition	Degradation (%)	References
16 Priority PAHs (with nitrate and sulfate)	Anaerobic	Bacteria	Sediment Anaerobic	37, 21, and 28%	[77]
Phenanthrene, Pyrene, and Benzo(a) pyrene	Aerobic	Bacterial–algal synergy	Soil slurry Aerobic	100%	[78]
Indeno[1,2,3-cd]pyrene	Aerobic	fungi	Liquid medium Aerobic	91%	[79]
Anthracene, Fluorene, Phenanthrene, and Pyrene	Aerobic	Extremophiles	Liquid medium At 50 °C Aerobic	96, 86, 54, and 71%	[80]
Pyrene	Anaerobic	facultative bacteria	<i>Pseudomonas</i> sp. JP1 and <i>Klebsiella</i> sp. LZ6	-	[81]
Pyrene	Aerobic	Bacteria	<i>Mycobacterium vanbaalenii</i> PRY-1 and <i>Mycobacterium</i> sp. KMS	-	[81]
Anthracene, Acenaphthene, Fluorene, Phenanthrene, Fluoranthene, and Pyrene	Aerobic	Non-ligninolytic fungi	Liquid medium Aerobic	71, 78, 70, 47, 52, and 62%	[82]

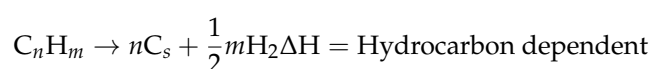
7. Reactions Involved in the Breakdown of Hydrocarbons

Catalytic (metal or metal-based) or non-catalytic (thermal or plasma) procedures are described in the literature concerning hydrocarbon breakdown. Hydrogen has been used as a fuel for decades to make carbon black via the thermal breakdown of CH₄. Researchers have tried to lower the maximum temperature at which hydrocarbons can be thermally broken down using catalysts. Transition and noble metals such as Ni, Fe, Pd, and Co are often used as catalysts. Separating hydrocarbons into hydrogen and carbon is the focus of several studies employing carbon-based materials. Benefits of this approach include reduced CO₂ and CO emissions, cleaner carbon byproducts, and the ability to use a wider variety of fuels. The main barrier to catalytic technology's widespread deployment in the industry is carbon accumulation on the catalyst surface [20,83–85]. Methane breakdown

for successive CO₂-free H₂ generation has been the primary focus of the studies. However, research on mobile applications to improve ICE efficiency or future fuel cell use is scant. To capture the energy of a highly active catalyst, it is necessary to construct a practical reactor. There are several suggestions and patents to be found in the literature. Undoubtedly, some have not yet undergone thorough testing and are thus unfit for H₂ production. Radiation, fluidized-bed, tubular, fixed-bed, and fluidized-bed (FBR) reactors are among the kinds now being researched; FBR reactors are seen to be the most promising for large-scale operation. Rapid heat and mass transfer occur between the catalyst particles and the gas due to the FBR reactor's bed of microscopic catalyst particles behaving like a well-mixed liquid. However, additional research is necessary before FBR may be used for marine applications. Several concerns must be addressed [19,86], including heat input, catalyst elimination, and regeneration. The most economic literature on hydrocarbon H₂ decomposition discusses the economics of H₂ generation for large-scale uses, whereas there are few references for shipboard applications. However, the cost of producing H₂ is contingent upon the quality and selling price of the carbon generated.

Decomposition Reaction and Energy Requirements

The several methods for extracting H₂ and carbon from hydrocarbons have been extensively discussed in some papers [25,32,87,88]. The hydrocarbon stream was pyrolyzed in thermal procedures at high temperatures (over 1400 °C) by partially combusting hydrocarbons and quenching with water to prevent a reverse reaction. The yield was also relatively low, as was productivity. The challenge of consistently managing carbon buildup posed a barrier to hydrocarbon breakdown. There is no need for secondary reactors for water gas shift, preferential oxidation, or CO₂ removal since no water or air is present, preventing the generation of carbon oxides (such as CO or CO₂). Thus, there are considerable decreases in emissions as a consequence of this technique. Various gaseous and liquid hydrocarbon fuels may be used in the breakdown process, providing an H₂ stream with up to 95% volumetric purity (Remanent methane). As far as carbon sequestration is concerned, solid carbon is simpler to separate, handle, transport, and store than CO₂ gas. Carbon may be extracted and sequestered by thermal cracking. Carbon sequestration energy loss is thermal cracking's most significant drawback. Cracking may be the most effective approach for natural gas and other hydrocarbons with high H₂/C ratios. This simplified net reaction represents the thermal cracking of hydrocarbons:



Other compounds could potentially develop depending on the reaction kinetics and the presence of impurities in the starting materials. A gas phase high in hydrogen and a condensed phase high in carbon are the results of the procedure mentioned above. The strong C-H bond is the fundamental issue in the cleavage of CH₄, for instance, which is a somewhat endothermic reaction:



The thermal energy needed to make one mole of H₂ is less than in SMR, with 37.8 kJ/mole of H₂. The endothermic process may be driven by less than 10% of methane's heating value. The CO₂ emissions from the process might be as low as 0.05 mol CO₂/mol H₂ if CH₄ is utilized as the process fuel, as opposed to 0.43 mol CO₂/mol H₂ with SMR. Theoretically, if 16% of the H₂ product is burnt to provide process heat, CO₂ emissions might be eliminated. To provide heat for the degrading process, Muradov et al. [88] looked at a variety of technological approaches, including internal, external, and autothermal (or thermoneutral) solutions (Figure 5).

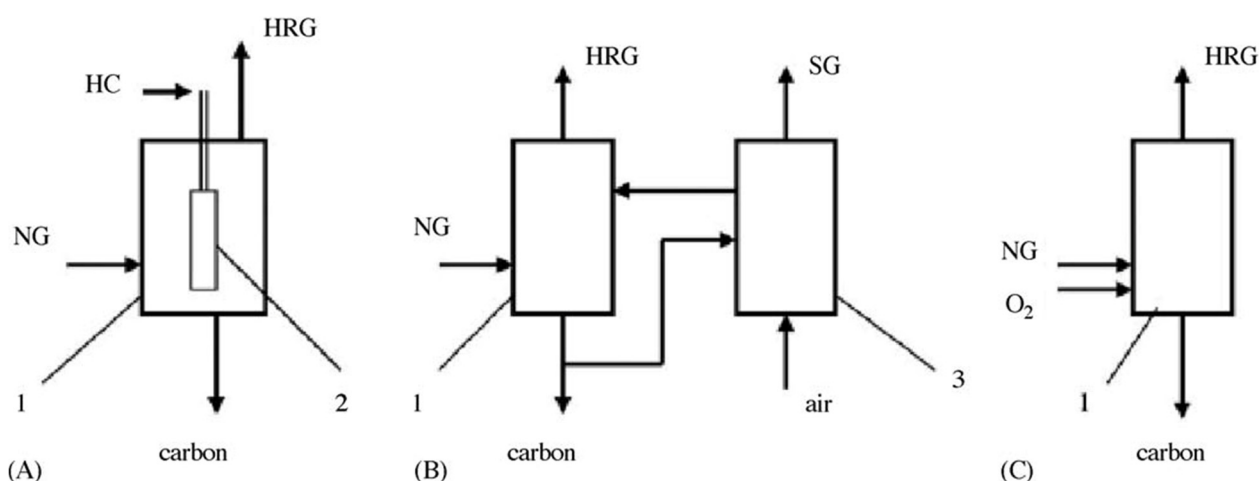


Figure 5. Internal (A), external (B), and thermoneutral (C) are the three options for heat input (C). For the heat input necessary for CH_4 breakdown, there are three options. Exhaust gases, heat transfer medium, and hydrogen-rich gas (NG HRG) are all used. Methane breakdown reactor, reactor heating, and catalyst particle heating are the three components (License Number: 5411970124733) [88].

The auto-thermal option is superior to other strategies because of its versatility and simplicity. Two potential technological approaches are shown in Figure 6 for the CH_4 degrading process employing an FBR with internal or exterior heat input [89]. Heat is produced in the FBR reaction zone according to the concept (A) in Figure 6 by heating appliances (such as heat pipes, catalytic burners, heat exchangers, etc.) that are within the reaction zone (in certain situations, the primary heat source may be outside the reactor) [89].

Muradov et al. [19] considered the potential of adding heat by injecting a very modest quantity of O_2 to create sufficient heat for the endothermic breakdown of CH_4 . In contrast, since syngas is not produced as a byproduct of the reaction, the procedure would utilize around two to three times less O_2 than POX. As with fluid catalytic cracking and fluidized bed coking, concept (B) in Figure 6 depicts the process flow of the decomposition process with external heat input. A heater and a reactor are stationary fluid containers in which the fluidized catalyst particles circulate [19]. Using a theoretical method, Bautista et al. [32] calculated the temperature of CH_4 decay in a planar stagnation point flow over a catalytic carbon surface. In five heterogeneous processes, comprising adsorption and desorption reactions, the heterogeneous reaction mechanism is used to represent the creation of H_2 . The conservation equations for the species mass, momentum, and energy in the gas phase were solved while taking the decomposition temperature into account. The crucial temperature parameters for catalytic thermal breakdown were therefore discovered using a high activation energy analysis for the desorption kinetics of the adsorbed hydrogen component. As a function of the surface coverages of the product species, computational studies in particular demonstrated that the decomposition temperature increased with the velocity gradient of the steady-state flow.

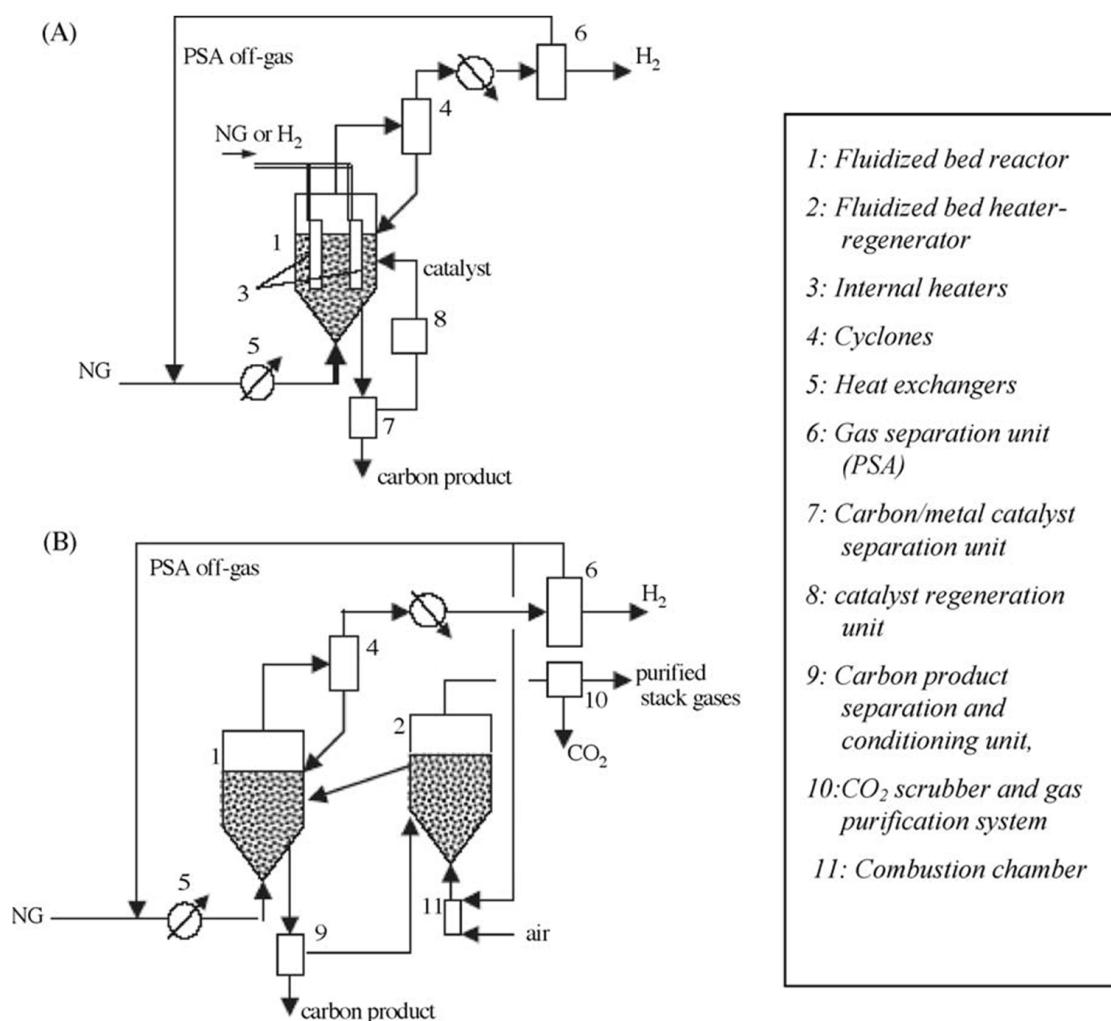


Figure 6. H₂ and carbon are created by catalytic cracking of natural gas using both endothermic reactions (A) and exothermic reactions (B) (License Number: 5411971299711) [19].

8. Enzyme-Based Decomposition of Hydrocarbons

Although aromatic organic compounds have low solubility, inhibit metabolites, produce toxic dead-end metabolites, and the presence of preferred substrates, aromatic organic compounds do not biodegrade at a faster rate than other organic compounds. There are also a few reasons why aromatic organic compounds do not biodegrade as quickly as others [90]. To circumvent most of the disadvantages of microorganisms, the use of enzymatic proteins may be a viable option. Enzyme-based biocatalysis is often referred to as white biotechnology. The use of enzymes in bioremediation has several advantages, including the following: 1. They are not inhibited by microbial metabolic inhibitors and can be used under adverse environmental conditions; 2. They are activated at low contaminant concentrations and remain active in the presence of antimicrobial agents; 3. Due to their small size, they are more mobile than microorganisms; 4. Enzymes can act intracellularly or extracellularly in the presence or outside the cell; 5. Hydrolases, dehalogenases, transferases, and oxidoreductases are the most important enzymes used for bioremediation, mainly found in bacteria, fungi, plants, and plant-associated microbes. These enzymes cleave ester, amide, and peptide bonds to produce soft or less harmful compounds [91]. Microorganisms have some enzymes that degrade hydrocarbons. They are capable of using biotechnology. For example, naphthalene dioxygenase is the most crucial enzyme for degrading naphthalene, which subsequently degrades aromatic hydrocarbons. Cytochrome P450 is a monooxygenase enzyme used in a variety of industries [46]. By measuring enzymes, one can study the

metabolic activities of microbial populations. Leucine aminopeptidase (LAP) is involved in the degradation of proteins, B-glucosidase (BG) in the degradation of carbohydrates, and alkaline phosphatase (AP) in the release of phosphorus from organic molecules.

By analyzing these enzymes, the rate of degradation can be calculated [92]. A superfamily of widely distributed co-thiolate monooxygenases, including cytochrome P450 alkane hydroxylase, is vital for microbial degradation of petroleum, chlorinated hydrocarbons, fuel additives, and other substances. Enzyme systems are required for oxygenation of the substrate and initiation of biodegradation, and the need varies depending on the length of the chain. In general, higher eukaryotes have a number of different P450 families and many P450 forms that can cooperate in the metabolic conversion of isoforms of a given substrate. Only microbes possess many variants of this P450 diversity [93–95]. Cytochrome P450 enzyme systems play a role in the biodegradation of petroleum hydrocarbons. Figure 7 shows the three main degradation processes of PAH by fungi and bacteria.

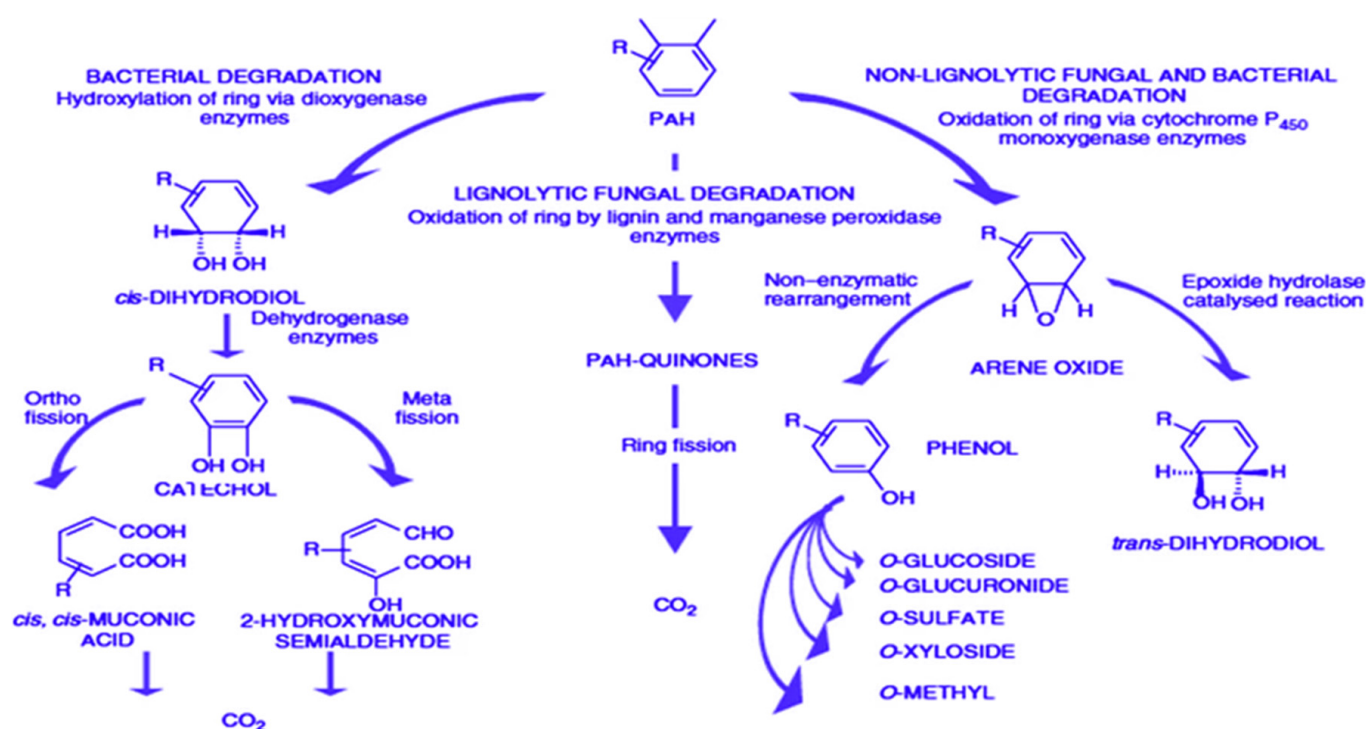


Figure 7. Three central PAH breakdown mechanisms by bacteria and fungus [96].

Some aromatic hydrocarbons (HCs) are found in petroleum, such as BTEX, while naphthalene is the simplest form of PAHs with its two rings. No single microorganism has been able to utilize high molecular weight aromatic compounds such as benzopyrene as the sole source of energy, although co-metabolic activities have been reported. An enzyme system that includes dioxygenase catalyzes the oxidation of arenes in aerobic bacteria to produce vicinal *cis*-dihydrodiols as the first intermediate of aromatic HC degradation. Byproducts of dihydroxylation undergo ring cleavage by intra- or extra-diol ring cleaving dioxygenases either through an orthocleavage pathway or a metacleavage pathway, which results in intermediates such as protocatechuate and catechols when benzene is used as an example. These substances enter the TCA cycle and are made available to the cell as carbon or energy sources through the breakdown of metabolites such as succinate, acetate, pyruvate, and acetaldehyde. Microbes can attack aliphatic or aromatic fractions of crude oil during degradation [90]. In recent years, extensive studies have been conducted on ligninolytic fungi because they produce particular enzymes for their substrates. In addition to degrading and mineralizing various organic pollutants, this has evolved due to the irregular structure of lignin. Recent studies have shown that these fungi can oxidize PAHs

via extracellular peroxidases. As a result of enzyme-mediated lignin peroxidation, fungal lignin peroxidases directly oxidize a number of PAHs. In addition, thein is directly co-oxidized by manganese peroxidases in fungi. PAHs cannot be degraded by fungi as rapidly or effectively as bacteria, but fungi are very nonspecific and capable of degrading a wide range of xenobiotics. Many fungi in soil litter can aid in removing PAHs in soil by growing into the soil and spreading throughout the solid matrix. It follows that ligninolytic fungi play an important ecological role in bioremediation. In addition, many fungal enzymes can degrade PAHs, including MnP, LiP, and laccase [97].

8.1. Factors Affecting the Decomposition of Petroleum Hydrocarbons

Several recognized variables influence the biodegradation of petroleum hydrocarbons. Some studies examine the different parameters that affect the rate of crude oil biodegradation. Because the molecules are too massive and complicated to be destroyed by microbes, oils containing substantial levels of heavy chemicals may not be readily biodegradable. The existence of microorganisms with sufficient metabolic capabilities is a crucial need. The ideal growth and biodegradation rate of hydrocarbons may be enhanced when these microorganisms are present, but only if there is enough concentration of nutrients and oxygen and the pH is optimal. Physical and chemical properties of the oil and environmental factors such as temperature, nutrients, oxygen, biodegradability, photooxidation, bioavailability, soil moisture, soil acidity, and alkalinity, water availability and effects of oil absorption in the region are crucial to the success of biodiversity [75,98]. Furthermore, temperature, nutrient availability, moisture content, and oxygen demand can influence the biodegradation process in the soil [90].

8.1.1. Temperature

An optimal temperature environment is required to grow hydrocarbon-degrading organisms (bacteria). It is reported that hydrocarbons are most effectively degraded at temperatures between 20 and 300 degrees Celsius [99]. Temperature affects not only the moisture content of the soil but also its retention potential. An increase in temperature leads to a rise in the rate of biodegradation, while a decrease in temperature leads to a reduction in the rate of biodegradation [100].

8.1.2. Nutrients

Based on the quality and vital requirements of the microorganisms that degrade HC, nutrients are classified into macro-, micro-, and trace elements. There are three primary macronutrients in microbial cells: Carbon, Phosphorus, and Nitrogen, which account for 14% of their dry weight. It should be noted that HC-degrading organisms do not require several micronutrient groups, including iron, cobalt, manganese, copper, and zinc [101]. HC-containing oils reduce the accessibility of soil nutrients for plant growth. HC-contaminated sites always have nutrients for microbial growth and organic substrate additives that serve as electron donors for bioremediation [100].

8.1.3. pH

Hydrocarbon degradation tends to occur at pH values between 6 and 8 [99]. Microorganisms and bacteria grow less rapidly at a pH lower than optimal. Due to the pH-dependent nature of enzymes, the degradability of HCs compounds is dependent on the enzymes [102]. A certain type of fungus is more capable of biodegrading hydrocarbons at a pH of 7 than bacteria, which can only degrade hydrocarbons at a pH of 5 [90].

8.1.4. Oxygen

Anaerobic and aerobic conditions are involved in the degradation of hydrocarbons. When microorganisms perform aerobic respiration, oxygen is the final electron acceptor in metabolic reactions and oxidation (reduction). When microorganisms perform anaerobic respiration, nitrate, iron, sulfate, and carbon dioxide are produced as a result of aerobic

respiration, and toxic substances/compounds are degraded into non-toxic substances such as CO₂ and water. When hydrocarbon compounds are exposed to aerobic conditions, they are degraded more rapidly than under anaerobic conditions, and then they are degraded to water and carbon dioxide. Consequently, bioremediation is more likely to occur when oxygen levels increase [90].

8.2. Kinetics for the Biodegradation of PAHs

The composition of soil microflora determines the diversity and activity of soil microflora, which is directly related to the effectiveness of soil microflora in degrading polycyclic aromatic hydrocarbons and other compounds. It is also important to note that soil properties influence the strength of PAH interaction with soil compounds [103]. *Cunninghamella echinulata* efficiently degrades PAHs in the presence of these nutrients, whereas other native microbes do not. In addition, the rate at which contaminant concentrations change depends on the contaminant concentrations in the soil in a first-order reaction system, and the time prediction for degradation depends on the type of microorganism and contaminant concentration. The time for bioremediation of polluted soils varies greatly depending on the microorganisms, the type of pollutant, and its concentration. Monitoring biomass, conducting respiration studies, and investigating the ways in which the different organisms interact is necessary to improve more appropriate kinetic models. Although bioremediation has a higher success rate than synthetic methods, kinetics remain poorly understood, and fungi use in bioremediation is becoming more difficult [104]. Several enzymes are involved in fungal degradation exhibiting maximum activity at different temperatures. Monitoring the kinetics of different fungal strains' degradation is a complex procedure, but most have good degradation ability at mesophilic temperatures. Pretreatment at high temperatures can increase the degradation rate by volatilizing contaminants and reducing the partition coefficient between soil and water. This leads to increased dissolution of the contaminants and, thus, increased degradation [91].

8.3. Overview of Sludge Management Methods PAHs

The disposal of oily sludge should generally be done in three stages. The objectives of this project are (1) to reduce the amount of oil sludge generated by the petroleum industry, (2) to recover and recycle valuable fuel from existing oil sludge, and (3) to dispose of residues that cannot be recycled. Currently, it is not being implemented. Of the treatment stages, the first aims to prevent the generation of oily sludge and reduce its production volume, and the next two aim to effectively treat existing oily sludge, which is the subject of this study. Different methods have been developed for the treatment of oily sludge, which is shown in Figure 8.

Processes such as thickening, dewatering, and drying of sewage sludge primarily reduce the water content of the sludge, and these processes do not significantly affect the amount of PAHs [106]. In the composting of dewatered sewage sludge cake, aeration promotes mechanical dewatering, which improves the degradation of PAHs during biodegradation [107]. Cho et al. [108] showed in their report [108] that acid chemical digestion can increase the bioavailable fraction PYR from 59.1% to 68.7% in raw sludge, and the biological natural process of *Acidithiobacillus ferrooxidans* increases it to 79.3% by damaging the semi-permeable membranes of bacterial cells. Anaerobic digestion can treat the sludge in four stages: hydrolysis, acidification, acetogenesis, and methanogenesis, producing energy. While anaerobic digestion is relatively effective in removing PAHs, the degree of effectiveness varies from case to case. Anaerobic digestion of sewage sludge by Siebielska et al. [109] showed removal efficiencies of 88.9% for NAP, 38.3% for PHE, 40.7% for PYR, and 39.2% for bread dough. Mezzanotte, Anzano, Collina, Marazzi, and Lasagni [110] reported that anaerobic digestion of sewage sludge removed ACY, CHY, BkF, NAP, and BaF compared to ACE, ANT, FLU, IcdP, BaA, and BaP.

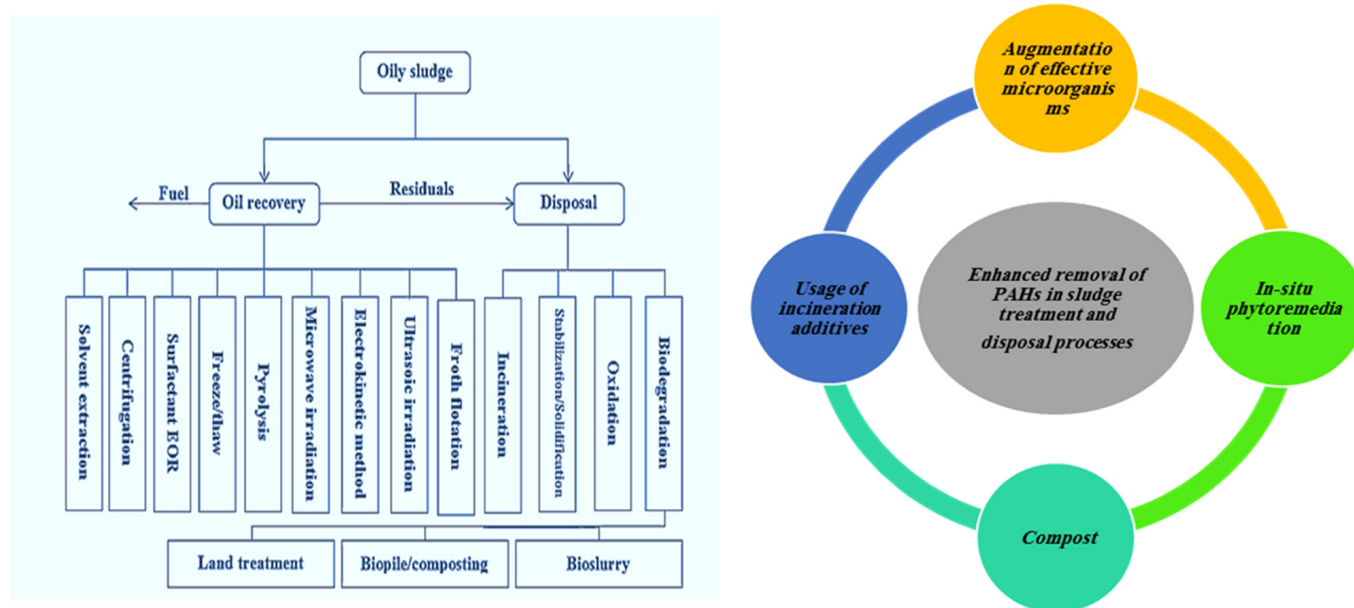


Figure 8. Overview of oily sludge treatment methods (License Number: 5435450889910) [105].

8.4. Challenges, Limitations, and Future Perspective

The present study has some limitations described in the literature. Additional research must be conducted on PAH elimination and transformation under anaerobic conditions, especially for high molecular weight PAHs, because of the limited understanding of anaerobic removal pathways, kinetics, enzyme regulation, and genetic regulation during wastewater and sludge treatment. In addition, most improved removal processes have performed satisfactorily at the laboratory scale. A laboratory-scale treatment system differs from a standard treatment system in many ways. The results of laboratory-scale tests must be applied to a treatment system. It would be helpful if this could be done more practically. Given the technical and economic challenges of cleaning these polluted sites using physical and chemical methods, biodegradation appears to be an appropriate solution [21]. However, biodegradation programs have a number of limitations, including the properties of the contaminants, the low performance of microbial communities under certain conditions, and the low bioavailability of the contaminants. Some industries are susceptible to PAH contamination. Several treatment methods for PAH-contaminated soils have been developed to remediate such sites. These treatment methods are very efficient when applied at a field scale. For example, to select an appropriate remediation method, it is crucial to know the conditions of the contaminated site, such as the type of contaminants present, soil properties, and weather conditions, since some methods are ineffective for areas with low permeability or mixed contaminants. In addition to these site-specific conditions, the choice of remediation technology also depends on its advantages, limitations, cost of alternative remediation methods, feasibility, and likely environmental impacts. Therefore, choosing the best remediation method for a field-scale application is very important for removing PAH from contaminated sites [107]. However, it should be noted that each remediation method has its advantages and limitations, and no single remediation method is capable of removing PAHs under all circumstances. By using integrated treatment technologies, the efficiency of PAH degradation or removal of PAHs can be improved by integrating two or more remediation methods in future research for different soil types. The condition of PAH-contaminated sites also needs to be accurately determined through extensive research [111].

9. Conclusions

Hydrocarbon contaminants are significant because their poor reactivity makes them difficult to break down, and their hydrophobic qualities need solvents before bacteria can degrade them. These persistent organic pollutants pose a grave risk to human health and the environment. Biodegradability is crucial for decreasing the effect of petroleum hydrocarbons in contaminated settings. The environment and living beings face significant danger from petroleum pollution. These pollutants reach the environment through a variety of routes, such as natural oil spills from the seabed, imbalanced water discharges from tankers, maritime traffic, tanker accidents, oil refining, drilling, and production from oil wells, and degrade slowly. Bioremediation has been offered as a practical, cost-effective, and adaptable physical and chemical control alternative. Bioremediation is an interdisciplinary technique, and its effectiveness depends on a team of experts from several disciplines, including microbiology, engineering, ecology, geology, and chemistry. An improved understanding of microbial ecology, physiology, evolution, biochemistry, and genetics boosts the success rate of recovering microbial metabolites for environmental applications before bioremediation. In general, two approaches are employed to supply bacteria with a substrate for hydrocarbon contamination. The first approach is adsorption by direct cell contact with hydrocarbons, and the second is combining the biosurfactant by direct cell contact with the hydrocarbons. Individual oleophilic microorganisms or consortia of microorganisms may be used to regulate the polluted environment by biodegrading these pollutants. The catabolic routes (aerobic/anaerobic) involved in biodegradation offer a means to design effective solutions for the bioremediation of petroleum hydrocarbon environmental pollutants.

Author Contributions: S.M.M. and A.G. developed the idea and structure of the review article. S.A.H. and M.S. wrote the manuscript and collected the materials from databases. V.R. and C.W.L., W.-H.C. and A.G. revised and improved the manuscript. A.G. and S.M.M. supervised the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This work is sponsored by Ministry of Science and Technology, Taiwan (grant number: MOST 110-2628-E-011-003, MOST 109-2923-E-011-003-MY, MOST 111-NU-E-011-001-NU).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lawal, A.T. Polycyclic aromatic hydrocarbons. A review. *Cogent Environ. Sci.* **2017**, *3*, 1339841. [[CrossRef](#)]
2. Zhang, X.; Yang, L.; Zhang, H.; Xing, W.; Wang, Y.; Bai, P.; Zhang, L.; Hayakawa, K.; Toriba, A.; Wei, Y. Assessing approaches of human inhalation exposure to polycyclic aromatic hydrocarbons: A review. *Int. J. Environ. Res. Public Health* **2021**, *18*, 3124. [[CrossRef](#)] [[PubMed](#)]
3. Abdel-Shafy, H.I.; Mansour, M.S. A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. *Egypt. J. Pet.* **2016**, *25*, 107–123. [[CrossRef](#)]
4. Mallah, M.A.; Changxing, L.; Mallah, M.A.; Noreen, S.; Liu, Y.; Saeed, M.; Xi, H.; Ahmed, B.; Feng, F.; Mirjat, A.A. Polycyclic aromatic hydrocarbon and its effects on human health: An updated review. *Chemosphere* **2022**, *296*, 133948. [[CrossRef](#)] [[PubMed](#)]
5. Sarkar, D.; Ferguson, M.; Datta, R.; Birnbaum, S. Bioremediation of petroleum hydrocarbons in contaminated soils: Comparison of biosolids addition, carbon supplementation, and monitored natural attenuation. *Environ. Pollut.* **2005**, *136*, 187–195. [[CrossRef](#)] [[PubMed](#)]
6. Sniegowski, K.; Vanhecke, M.; D’Huys, P.-J.; Braeken, L. Potential of activated carbon to recover Randomly-methylated-B-cyclodextrin solution from waste water originating from in situ soil flushing. In Proceedings of the Aquaconsol, Barcelona, Spain, 16–19 April 2013.
7. Xu, X.; Liu, W.; Tian, S.; Wang, W.; Qi, Q.; Jiang, P.; Gao, X.; Li, F.; Li, H.; Yu, H. Petroleum hydrocarbon-degrading bacteria for the remediation of oil pollution under aerobic conditions: A perspective analysis. *Front. Microbiol.* **2018**, *9*, 2885. [[CrossRef](#)]

8. Saravanan, A.; Kumar, P.S.; Vo, D.-V.N.; Jeevanantham, S.; Karishma, S.; Yaashikaa, P. A review on catalytic-enzyme degradation of toxic environmental pollutants: Microbial enzymes. *J. Hazard. Mater.* **2021**, *419*, 126451. [\[CrossRef\]](#)
9. Mousavi, S.M.; Hashemi, S.A.; Gholami, A.; Omidifar, N.; Zarei, M.; Bahrani, S.; Yousefi, K.; Chiang, W.-H.; Babapoor, A. Bioinorganic synthesis of polyrhodanine stabilized Fe₃O₄/Graphene oxide in microbial supernatant media for anticancer and antibacterial applications. *Bioinorg. Chem. Appl.* **2021**, *2021*, 9972664. [\[CrossRef\]](#)
10. Ossai, I.C.; Ahmed, A.; Hassan, A.; Hamid, F.S. Remediation of soil and water contaminated with petroleum hydrocarbon: A review. *Environ. Technol. Innov.* **2020**, *17*, 100526.
11. Eze, M.O.; Hose, G.C.; George, S.C.; Daniel, R. Diversity and metagenome analysis of a hydrocarbon-degrading bacterial consortium from asphalt lakes located in Wietze, Germany. *AMB Express* **2021**, *11*, 89. [\[CrossRef\]](#)
12. Azhdari, R.; Mousavi, S.M.; Hashemi, S.A.; Bahrani, S.; Ramakrishna, S. Decorated graphene with aluminum fumarate metal organic framework as a superior non-toxic agent for efficient removal of Congo Red dye from wastewater. *J. Environ. Chem. Eng.* **2019**, *7*, 103437. [\[CrossRef\]](#)
13. Gayathiri, E.; Prakash, P.; Karmegam, N.; Varjani, S.; Awasthi, M.K.; Ravindran, B. Biosurfactants: Potential and eco-friendly material for sustainable agriculture and environmental safety—A review. *Agronomy* **2022**, *12*, 662. [\[CrossRef\]](#)
14. Fathepure, B.Z. Recent studies in microbial degradation of petroleum hydrocarbons in hypersaline environments. *Front. Microbiol.* **2014**, *5*, 173. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Mousavi, S.M.; Zarei, M.; Hashemi, S.A.; Ramakrishna, S.; Chiang, W.-H.; Lai, C.W.; Gholami, A. Gold nanostars-diagnosis, bioimaging and biomedical applications. *Drug Metab. Rev.* **2020**, *52*, 299–318. [\[CrossRef\]](#)
16. Lin, C.; Gan, L.; Chen, Z.-L. Biodegradation of naphthalene by strain *Bacillus fusiformis* (BFN). *J. Hazard. Mater.* **2010**, *182*, 771–777. [\[CrossRef\]](#)
17. Abootalebi, S.N.; Saeed, A.; Gholami, A.; Mohkam, M.; Kazemi, A.; Nezafat, N.; Mousavi, S.M.; Hashemi, S.A.; Shorafa, E. Screening, characterization and production of thermostable alpha-amylase produced by a novel thermophilic *Bacillus megaterium* isolated from pediatric intensive care unit. *J. Environ. Treat. Tech.* **2020**, *8*, 952–960.
18. Mohkam, M.; Rasoul-Amini, S.; Shokri, D.; Berenjian, A.; Rahimi, F.; Sadraei, M.; Khalvati, B.; Gholami, A.; Ghasemi, Y. Characterization and in vitro probiotic assessment of potential indigenous *Bacillus* strains isolated from soil rhizosphere. *Minerva Biotechnol.* **2016**, *28*, 19–28.
19. Ahmed, S.; Aitani, A.; Rahman, F.; Al-Dawood, A.; Al-Muhaish, F. Decomposition of hydrocarbons to hydrogen and carbon. *Appl. Catal. A Gen.* **2009**, *359*, 1–24. [\[CrossRef\]](#)
20. Varjani, S.J.; Upasani, V.N. A new look on factors affecting microbial degradation of petroleum hydrocarbon pollutants. *Int. Biodeterior. Biodegrad.* **2017**, *120*, 71–83. [\[CrossRef\]](#)
21. Megharaj, M.; Ramakrishnan, B.; Venkateswarlu, K.; Sethunathan, N.; Naidu, R. Bioremediation approaches for organic pollutants: A critical perspective. *Environ. Int.* **2011**, *37*, 1362–1375. [\[CrossRef\]](#)
22. Mousavi, S.M.; Hashemi, S.A.; Yari Kalashgrani, M.; Omidifar, N.; Lai, C.W.; Vijayakameswara Rao, N.; Gholami, A.; Chiang, W.-H. The Pivotal Role of Quantum Dots-Based Biomarkers Integrated with Ultra-Sensitive Probes for Multiplex Detection of Human Viral Infections. *Pharmaceuticals* **2022**, *15*, 880. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Mousavi, S.-M.; Nejad, Z.M.; Hashemi, S.A.; Salari, M.; Gholami, A.; Ramakrishna, S.; Chiang, W.-H.; Lai, C.W. Bioactive agent-loaded electrospun nanofiber membranes for accelerating healing process: A review. *Membranes* **2021**, *11*, 702. [\[CrossRef\]](#)
24. Gholami, A.; Mohammadi, F.; Ghasemi, Y.; Omidifar, N.; Ebrahimezhad, A. Antibacterial activity of SPIONs versus ferrous and ferric ions under aerobic and anaerobic conditions: A preliminary mechanism study. *IET Nanobiotechnol.* **2020**, *14*, 155–160. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Muradov, N. Emission-free fuel reformers for mobile and portable fuel cell applications. *J. Power Sources* **2003**, *118*, 320–324. [\[CrossRef\]](#)
26. Atlas, R.M.; Hazen, T.C. *Oil Biodegradation and Bioremediation: A Tale of the Two Worst Spills in US History*; ACS Publications: Columbus, OH, USA, 2011.
27. Mousavi, S.M.; Hashemi, S.A.; Ghahramani, Y.; Azhdari, R.; Yousefi, K.; Gholami, A.; Fallahi Nezhad, F.; Vijayakameswara Rao, N.; Omidifar, N.; Chiang, W.-H. Antiproliferative and Apoptotic Effects of Graphene Oxide@ AlFu MOF Based Saponin Natural Product on OSCC Line. *Pharmaceuticals* **2022**, *15*, 1137. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Vidonish, J.E.; Zygourakis, K.; Masiello, C.A.; Sabadell, G.; Alvarez, P.J. Thermal treatment of hydrocarbon-impacted soils: A review of technology innovation for sustainable remediation. *Engineering* **2016**, *2*, 426–437. [\[CrossRef\]](#)
29. Premnath, N.; Mohanrasu, K.; Rao, R.G.R.; Dinesh, G.; Prakash, G.S.; Ananthi, V.; Ponnuchamy, K.; Muthusamy, G.; Arun, A. A crucial review on polycyclic aromatic Hydrocarbons-Environmental occurrence and strategies for microbial degradation. *Chemosphere* **2021**, *280*, 130608.
30. Eldos, H.I.; Zouari, N.; Saeed, S.; Al-Ghouti, M.A. Recent advances in the treatment of PAHs in the environment: Application of nanomaterial-based technologies. *Arab. J. Chem.* **2022**, *15*, 103918. [\[CrossRef\]](#)
31. Johnston, J.E.; Lim, E.; Roh, H. Impact of upstream oil extraction and environmental public health: A review of the evidence. *Sci. Total Environ.* **2019**, *657*, 187–199. [\[CrossRef\]](#)
32. Bautista, O.; Méndez, F.; Trevino, C. Theoretical analysis of the direct decomposition of methane gas in a laminar stagnation-point flow: CO₂-free production of hydrogen. *Int. J. Hydrogen Energy* **2008**, *33*, 7419–7426. [\[CrossRef\]](#)

33. Luo, L.; Wang, P.; Lin, L.; Luan, T.; Ke, L.; Tam, N.F.Y. Removal and transformation of high molecular weight polycyclic aromatic hydrocarbons in water by live and dead microalgae. *Process Biochem.* **2014**, *49*, 1723–1732. [\[CrossRef\]](#)
34. Loyeh, E.; Mohsenpour, R. Investigation of oil pollution on aquatic animals and methods of its prevention. *J. Aquac. Mar. Biol.* **2020**, *9*, 160–165.
35. Mohanty, M. Potential Applications of Biosurfactant from Marine Bacteria in Bioremediation. Master's Thesis, National Institute of Technology, Rourkela, India, 2013.
36. Alireza Hashemi, S.; Bahrani, S.; Mojtaba Mousavi, S.; Mojoudi, F.; Omidifar, N.; Bagheri Lankarani, K.; Arjmand, M.; Ramakrishna, S. Development of sulfurized Polythiophene-Silver Iodide-Diethyldithiocarbamate nanoflakes toward Record-High and selective absorption and detection of mercury derivatives in aquatic substrates. *Chem. Eng. J.* **2022**, *440*, 135896. [\[CrossRef\]](#)
37. Islam, M.S.; Tanaka, M. Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: A review and synthesis. *Mar. Pollut. Bull.* **2004**, *48*, 624–649. [\[CrossRef\]](#)
38. Kalashgarani, M.Y.; Babapoor, A. Application of nano-antibiotics in the diagnosis and treatment of infectious diseases. *Adv. Appl. NanoBio-Technol.* **2022**, *3*, 22–35.
39. Mousavi, S.M.; Hashemi, S.A.; Kalashgrani, M.Y.; Omidifar, N.; Bahrani, S.; Vijayakameswara Rao, N.; Babapoor, A.; Gholami, A.; Chiang, W.-H. Bioactive Graphene Quantum Dots Based Polymer Composite for Biomedical Applications. *Polymers* **2022**, *14*, 617. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Tam, N.F.; Wong, T.W.; Wong, Y. A case study on fuel oil contamination in a mangrove swamp in Hong Kong. *Mar. Pollut. Bull.* **2005**, *51*, 1092–1100. [\[CrossRef\]](#) [\[PubMed\]](#)
41. Mousavi, S.M.; Hashemi, S.A.; Iman Moezzi, S.M.; Ravan, N.; Gholami, A.; Lai, C.W.; Chiang, W.-H.; Omidifar, N.; Yousefi, K.; Behbudi, G. Recent advances in enzymes for the bioremediation of pollutants. *Biochem. Res. Int.* **2021**, *2021*, 5599204. [\[CrossRef\]](#)
42. Hall, J.; Matos, S.; Bachor, V. From green technology development to green innovation: Inducing regulatory adoption of pathogen detection technology for sustainable forestry. *Small Bus. Econ.* **2019**, *52*, 877–889. [\[CrossRef\]](#)
43. Hamouda, R.A.; Daassi, D.; Hassan, H.A.; Hussein, M.H.; El-Sheekh, M.M. Use of live microbes for oil degradation in situ. In *Advances in Oil-Water Separation*; Elsevier: Berlin/Heidelberg, Germany, 2022; pp. 297–317.
44. Hosseini, H.; Mousavi, S.M.; Wurm, F.R.; Goodarzi, V. Display of hidden properties of flexible aerogel based on bacterial cellulose/polyaniline nanocomposites with helping of multiscale modeling. *Eur. Polym. J.* **2021**, *146*, 110251. [\[CrossRef\]](#)
45. Safdel, M.; Anbaz, M.A.; Daryasafar, A.; Jamialahmadi, M. Microbial enhanced oil recovery, a critical review on worldwide implemented field trials in different countries. *Renew. Sustain. Energy Rev.* **2017**, *74*, 159–172. [\[CrossRef\]](#)
46. Abbasian, F.; Lockington, R.; Mallavarapu, M.; Naidu, R. A comprehensive review of aliphatic hydrocarbon biodegradation by bacteria. *Appl. Biochem. Biotechnol.* **2015**, *176*, 670–699. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Karigar, C.S.; Rao, S.S. Role of microbial enzymes in the bioremediation of pollutants: A review. *Enzym. Res.* **2011**, *2011*, 805187. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Sarsaiya, S.; Awasthi, S.K.; Jain, A.; Mishra, S.; Jia, Q.; Shu, F.; Li, J.; Duan, Y.; Singh, R.; Awasthi, M.K. Recent Developments in the Treatment of Petroleum Hydrocarbon and Oily Sludge from the Petroleum Industry. In *Biological Processing of Solid Waste*; CRC Press: Boca Raton, FL, USA, 2019; Volume 277.
49. Varner, P.M.; Gunsch, C.K. Properties affecting transfer and expression of degradative plasmids for the purpose of bioremediation. *Biodegradation* **2021**, *32*, 361–375. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Obayori, O.S.; Salam, L.B. Degradation of polycyclic aromatic hydrocarbons: Role of plasmids. *Sci. Res. Essays* **2010**, *5*, 4093–4106.
51. Das, N.; Chandran, P. Microbial degradation of petroleum hydrocarbon contaminants: An overview. *Biotechnol. Res. Int.* **2011**, *2011*, 941810. [\[CrossRef\]](#)
52. Al-Hawash, A.B.; Dragh, M.A.; Li, S.; Alhujaily, A.; Abbood, H.A.; Zhang, X.; Ma, F. Principles of microbial degradation of petroleum hydrocarbons in the environment. *Egypt. J. Aquat. Res.* **2018**, *44*, 71–76. [\[CrossRef\]](#)
53. Liu, X.; Li, Z.; Zhang, C.; Tan, X.; Yang, X.; Wan, C.; Lee, D.-J. Enhancement of anaerobic degradation of petroleum hydrocarbons by electron intermediate: Performance and mechanism. *Bioresour. Technol.* **2020**, *295*, 122305. [\[CrossRef\]](#)
54. Wilkes, H.; Buckel, W.; Golding, B.T.; Rabus, R. Metabolism of hydrocarbons in n-alkane-utilizing anaerobic bacteria. *Microb. Physiol.* **2016**, *26*, 138–151. [\[CrossRef\]](#)
55. Bahrani, S.; Hashemi, S.A.; Mousavi, S.M.; Azhdari, R. Zinc-based metal–organic frameworks as nontoxic and biodegradable platforms for biomedical applications: Review study. *Drug Metab. Rev.* **2019**, *51*, 356–377. [\[CrossRef\]](#)
56. Truskewycz, A.; Gundry, T.D.; Khudur, L.S.; Kolobaric, A.; Taha, M.; Aburto-Medina, A.; Ball, A.S.; Shahsavari, E. Petroleum hydrocarbon contamination in terrestrial ecosystems—Fate and microbial responses. *Molecules* **2019**, *24*, 3400. [\[CrossRef\]](#)
57. Mousavi, S.M.; Hashemi, S.A.; Kalashgrani, M.Y.; Gholami, A.; Omidifar, N.; Babapoor, A.; Vijayakameswara Rao, N.; Chiang, W.-H. Recent Advances in Plasma-Engineered Polymers for Biomarker-Based Viral Detection and Highly Multiplexed Analysis. *Biosensors* **2022**, *12*, 286. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Ghosal, D.; Ghosh, S.; Dutta, T.K.; Ahn, Y. Current state of knowledge in microbial degradation of polycyclic aromatic hydrocarbons (PAHs): A review. *Front. Microbiol.* **2016**, *7*, 1369. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Sharma, B.; Shukla, P. Futuristic avenues of metabolic engineering techniques in bioremediation. *Biotechnol. Appl. Biochem.* **2022**, *69*, 51–60. [\[CrossRef\]](#) [\[PubMed\]](#)
60. Zadeh, B.S.; Esmaeili, H.; Foroutan, R.; Mousavi, S.M.; Hashemi, S.A. Removal of Cd²⁺ from aqueous solution using eucalyptus sawdust as a bio-adsorbent: Kinetic and equilibrium studies. *J. Environ. Treat. Tech.* **2020**, *8*, 112–118.

61. Li, X.; Li, H.; Qu, C. A review of the mechanism of microbial degradation of petroleum pollution. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *484*, 012060. [\[CrossRef\]](#)
62. Mousavi, S.M.; Hashemi, S.A.; Bahrani, S.; Yousefi, K.; Behbudi, G.; Babapoor, A.; Omidifar, N.; Lai, C.W.; Gholami, A.; Chiang, W.-H. Recent advancements in polythiophene-based materials and their biomedical, geno sensor and DNA detection. *Int. J. Mol. Sci.* **2021**, *22*, 6850. [\[CrossRef\]](#)
63. Shen, T.; Pi, Y.; Bao, M.; Xu, N.; Li, Y.; Lu, J. Biodegradation of different petroleum hydrocarbons by free and immobilized microbial consortia. *Environ. Sci. Process. Impacts* **2015**, *17*, 2022–2033. [\[CrossRef\]](#)
64. Mousavi, S.M.; Hashemi, S.A.; Bahrani, S.; Sadrmousavi-Dizaj, A.; Arjmand, O.; Omidifar, N.; Lai, C.W.; Chiang, W.-H.; Gholami, A. Bioinorganic Synthesis of Sodium Polytungstate/Polyoxometalate in Microbial Kombucha Media for Precise Detection of Doxorubicin. *Bioinorg. Chem. Appl.* **2022**, *2022*, 2265108. [\[CrossRef\]](#)
65. Pinheiro Pires, A.P.; Arauzo, J.; Fonts, I.; Domine, M.E.; Fernández Arroyo, A.; Garcia-Perez, M.E.; Montoya, J.; Chejne, F.; Pfromm, P.; Garcia-Perez, M. Challenges and opportunities for bio-oil refining: A review. *Energy Fuels* **2019**, *33*, 4683–4720. [\[CrossRef\]](#)
66. Thavasi, R.; Jayalakshmi, S.; Banat, I.M. Application of biosurfactant produced from peanut oil cake by *Lactobacillus delbrueckii* in biodegradation of crude oil. *Bioresour. Technol.* **2011**, *102*, 3366–3372. [\[CrossRef\]](#) [\[PubMed\]](#)
67. Jafari, A.; Zamankhan, P.; Mousavi, S.M.; Henttinen, K. Multiscale modeling of fluid turbulence and flocculation in fiber suspensions. *J. Appl. Phys.* **2006**, *100*, 034901. [\[CrossRef\]](#)
68. Xu, D.; Zhang, K.; Li, B.-G.; Mbadinga, S.M.; Zhou, L.; Liu, J.-F.; Yang, S.-Z.; Gu, J.-D.; Mu, B.-Z. Simulation of in situ oil reservoir conditions in a laboratory bioreactor testing for methanogenic conversion of crude oil and analysis of the microbial community. *Int. Biodeterior. Biodegrad.* **2019**, *136*, 24–33. [\[CrossRef\]](#)
69. Kertesz, M.A.; Kawasaki, A.; Stolz, A. Aerobic hydrocarbon-degrading alphaproteobacteria: Sphingomonadales. In *Taxonomy, Genomics and Ecophysiology of Hydrocarbon-Degrading Microbes*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 105–124.
70. Niu, J.; Liu, Q.; Lv, J.; Peng, B. Review on microbial enhanced oil recovery: Mechanisms, modeling and field trials. *J. Pet. Sci. Eng.* **2020**, *192*, 107350. [\[CrossRef\]](#)
71. Omidifar, N.; Nili-Ahmadabadi, A.; Nakhostin-Ansari, A.; Lankarani, K.B.; Moghadami, M.; Mousavi, S.M.; Hashemi, S.A.; Gholami, A.; Shokripour, M.; Ebrahimi, Z. The modulatory potential of herbal antioxidants against oxidative stress and heavy metal pollution: Plants against environmental oxidative stress. *Environ. Sci. Pollut. Res.* **2021**, *28*, 61908–61918. [\[CrossRef\]](#) [\[PubMed\]](#)
72. Alegbeleye, O.O.; Opeolu, B.O.; Jackson, V.A. Polycyclic aromatic hydrocarbons: A critical review of environmental occurrence and bioremediation. *Environ. Manag.* **2017**, *60*, 758–783.
73. Chandra, S.; Sharma, R.; Singh, K.; Sharma, A. Application of bioremediation technology in the environment contaminated with petroleum hydrocarbon. *Ann. Microbiol.* **2013**, *63*, 417–431. [\[CrossRef\]](#)
74. Wartell, B.; Boufadel, M.; Rodriguez-Freire, L. An effort to understand and improve the anaerobic biodegradation of petroleum hydrocarbons: A literature review. *Int. Biodeterior. Biodegrad.* **2021**, *157*, 105156.
75. Meckenstock, R.U.; Boll, M.; Mouttaki, H.; Koelschbach, J.S.; Tarouco, P.C.; Weyrauch, P.; Dong, X.; Himmelberg, A.M. Anaerobic degradation of benzene and polycyclic aromatic hydrocarbons. *Microb. Physiol.* **2016**, *26*, 92–118. [\[CrossRef\]](#)
76. Kalashgrani, M.Y.; Harzand, F.V.; Javanmardi, N.; Nejad, F.F.; Rahmanian, V. Recent Advances in Multifunctional magnetic nano platform for Biomedical Applications: A mini review. *Adv. Appl. NanoBio-Technol.* **2022**, *3*, 31–37.
77. Hashemi, S.A.; Mousavi, S.M.; Bahrani, S.; Ramakrishna, S.; Hashemi, S.H. Picomolar-level detection of mercury within non-biological/biological aqueous media using ultra-sensitive polyaniline-Fe₃O₄-silver diethyldithiocarbamate nanostructure. *Anal. Bioanal. Chem.* **2020**, *412*, 5353–5365. [\[CrossRef\]](#) [\[PubMed\]](#)
78. Yang, X.; Li, E.; Liu, F.; Xu, M. Interactions of PAH-degradation and nitrate-/sulfate-reducing assemblages in anaerobic sediment microbial community. *J. Hazard. Mater.* **2020**, *388*, 122068. [\[CrossRef\]](#) [\[PubMed\]](#)
79. Subashchandrabose, S.R.; Venkateswarlu, K.; Venkidusamy, K.; Palanisami, T.; Naidu, R.; Megharaj, M. Bioremediation of soil long-term contaminated with PAHs by algal-bacterial synergy of *Chlorella* sp. MM3 and *Rhodococcus wratislaviensis* strain 9 in slurry phase. *Sci. Total Environ.* **2019**, *659*, 724–731. [\[CrossRef\]](#) [\[PubMed\]](#)
80. Ojha, N.; Mandal, S.K.; Das, N. Enhanced degradation of indeno(1,2,3-cd)pyrene using *Candida tropicalis* NN₄ in presence of iron nanoparticles and produced biosurfactant: A statistical approach. *3 Biotech* **2019**, *9*, 86. [\[CrossRef\]](#)
81. Mehrete, G.T.; Dastager, S.G.; Dharne, M.S. Biodegradation of mixed polycyclic aromatic hydrocarbons by pure and mixed cultures of biosurfactant producing thermophilic and thermo-tolerant bacteria. *Sci. Total Environ.* **2019**, *679*, 52–60. [\[CrossRef\]](#)
82. Elyamine, A.M.; Kan, J.; Meng, S.; Tao, P.; Wang, H.; Hu, Z. Aerobic and anaerobic bacterial and fungal degradation of pyrene: Mechanism pathway including biochemical reaction and catabolic genes. *Int. J. Mol. Sci.* **2021**, *22*, 8202. [\[CrossRef\]](#)
83. Holladay, J.D.; Hu, J.; King, D.L.; Wang, Y. An overview of hydrogen production technologies. *Catal. Today* **2009**, *139*, 244–260. [\[CrossRef\]](#)
84. Kalashgrani, M.Y.; Nejad, F.F.; Rahmanian, V. Carbon Quantum Dots Platforms: As nano therapeutic for Biomedical Applications. *Adv. Appl. NanoBio-Technol.* **2022**, *3*, 38–42.
85. Hosseini, H.; Mousavi, S.M. Bacterial cellulose/polyaniline nanocomposite aerogels as novel bioadsorbents for removal of hexavalent chromium: Experimental and simulation study. *J. Clean. Prod.* **2021**, *278*, 123817. [\[CrossRef\]](#)

86. Mousavi, S.M.; Hashemi, S.A.; Parvin, N.; Gholami, A.; Ramakrishna, S.; Omidifar, N.; Moghadami, M.; Chiang, W.-H.; Mazraeadoost, S. Recent biotechnological approaches for treatment of novel COVID-19: From bench to clinical trial. *Drug Metab. Rev.* **2021**, *53*, 141–170. [\[CrossRef\]](#)
87. Fulcheri, L.; Probst, N.; Flamant, G.; Fabry, F.; Grivei, E.; Bourrat, X. Plasma processing: A step towards the production of new grades of carbon black. *Carbon* **2002**, *40*, 169–176. [\[CrossRef\]](#)
88. Muradov, N.; Smith, F.; Huang, C.; Ali, T. Autothermal catalytic pyrolysis of methane as a new route to hydrogen production with reduced CO₂ emissions. *Catal. Today* **2006**, *116*, 281–288. [\[CrossRef\]](#)
89. Choudhary, T.; Goodman, D. Methane decomposition: Production of hydrogen and carbon filaments. *Catalysis* **2006**, *19*, 164–183.
90. Okolafor, F.; Ekhaise, F.O. Microbial Enzyme Remediation of Poly-Aromatic Hydrocarbon (PAH's): A review. *J. Int. Environ. Appl. Sci.* **2022**, *17*, 10–21.
91. Omidifar, N.; Nili-Ahmadabadi, A.; Gholami, A.; Dastan, D.; Ahmadimoghaddam, D.; Nili-Ahmadabadi, H. Biochemical and Histological Evidence on the Protective Effects of *Allium hirtifolium* Boiss (Persian Shallot) as an Herbal Supplement in Cadmium-Induced Hepatotoxicity. *Evid Based Complement Altern. Med.* **2020**, *2020*, 7457504. [\[CrossRef\]](#)
92. Hassanshahian, M.; Emtiazi, G.; Caruso, G.; Cappello, S. Bioremediation (bioaugmentation/biostimulation) trials of oil polluted seawater: A mesocosm simulation study. *Mar. Environ. Res.* **2014**, *95*, 28–38. [\[CrossRef\]](#)
93. van Beilen, J.B.; Funhoff, E.G. Expanding the alkane oxygenase toolbox: New enzymes and applications. *Curr. Opin. Biotechnol.* **2005**, *16*, 308–314. [\[CrossRef\]](#)
94. Van Beilen, J.B.; Funhoff, E.G. Alkane hydroxylases involved in microbial alkane degradation. *Appl. Microbiol. Biotechnol.* **2007**, *74*, 13–21. [\[CrossRef\]](#)
95. Zimmer, T.; Ohkuma, M.; Ohta, A.; Takagi, M.; Schunck, W.-H. The CYP52 Multigene Family of *Candida maltose* Encodes Functionally Diverse *n*-Alkane-Inducible Cytochromes P450. *Biochem. Biophys. Res. Commun.* **1996**, *224*, 784–789. [\[CrossRef\]](#)
96. Gupte, A.; Tripathi, A.; Patel, H.; Rudakiya, D.; Gupte, S. Bioremediation of polycyclic aromatic hydrocarbon (PAHs): A perspective. *Open Biotechnol. J.* **2016**, *10*, 363–378. [\[CrossRef\]](#)
97. Kadri, T.; Rouissi, T.; Brar, S.K.; Cledon, M.; Sarma, S.; Verma, M. Biodegradation of polycyclic aromatic hydrocarbons (PAHs) by fungal enzymes: A review. *J. Environ. Sci.* **2017**, *51*, 52–74. [\[CrossRef\]](#) [\[PubMed\]](#)
98. Ekpo, M.; Udofia, U. Rate of biodegradation of crude oil by microorganisms isolated from oil sludge environment. *Afr. J. Biotechnol.* **2008**, *7*, 4495–4499.
99. Iranzo, M.; Sainz-Pardo, I.; Boluda, R.; Sanchez, J.; Mormeneo, S. The use of microorganisms in environmental remediation. *Ann. Microbiol.* **2001**, *51*, 135–144.
100. Adams, G.; Tawari-Fufeyin, P.; Igelenyah, E. Bioremediation of spent oil contaminated soils using poultry litter. *Res. J. Eng. Appl. Sci.* **2014**, *3*, 124–130.
101. Graj, W.; Lisiecki, P.; Szulc, A.; Chrzanowski, L.; Wojtera-Kwiczor, J. Bioaugmentation with petroleum-degrading consortia has a selective growth-promoting impact on crop plants germinated in diesel oil-contaminated soil. *Water Air Soil Pollut.* **2013**, *224*, 1676. [\[CrossRef\]](#)
102. Wang, R.; Zhang, H.; Sun, L.; Qi, G.; Chen, S.; Zhao, X. Microbial community composition is related to soil biological and chemical properties and bacterial wilt outbreak. *Sci. Rep.* **2017**, *7*, 343. [\[CrossRef\]](#)
103. Cutright, T.J. Polycyclic aromatic hydrocarbon biodegradation and kinetics using *Cunninghamella echinulata* var. *elegans*. *Int. Biodeterior. Biodegrad.* **1995**, *35*, 397–408. [\[CrossRef\]](#)
104. Haritash, A.; Kaushik, C. Biodegradation aspects of polycyclic aromatic hydrocarbons (PAHs): A review. *J. Hazard. Mater.* **2009**, *169*, 1–15. [\[CrossRef\]](#)
105. Hu, G.; Li, J.; Zeng, G. Recent development in the treatment of oily sludge from petroleum industry: A review. *J. Hazard. Mater.* **2013**, *261*, 470–490.
106. Mailler, R.; Gasperi, J.; Patureau, D.; Vulliet, E.; Delgenes, N.; Danel, A.; Deshayes, S.; Eudes, V.; Guerin, S.; Moilleron, R. Fate of emerging and priority micropollutants during the sewage sludge treatment: Case study of Paris conurbation. Part 1: Contamination of the different types of sewage sludge. *Waste Manag.* **2017**, *59*, 379–393. [\[CrossRef\]](#)
107. Zhang, X.; Yu, T.; Li, X.; Yao, J.; Liu, W.; Chang, S.; Chen, Y. The fate and enhanced removal of polycyclic aromatic hydrocarbons in wastewater and sludge treatment system: A review. *Crit. Rev. Environ. Sci. Technol.* **2019**, *49*, 1425–1475. [\[CrossRef\]](#)
108. Zhou, W.; Lu, Y.; Jiang, S.; Xiao, Y.; Zheng, G.; Zhou, L. Impact of sludge conditioning treatment on the bioavailability of pyrene in sewage sludge. *Ecotoxicol. Environ. Saf.* **2018**, *163*, 196–204. [\[CrossRef\]](#) [\[PubMed\]](#)
109. Siebielska, I. Comparison of changes in selected polycyclic aromatic hydrocarbons concentrations during the composting and anaerobic digestion processes of municipal waste and sewage sludge mixtures. *Water Sci. Technol.* **2014**, *70*, 1617–1624. [\[CrossRef\]](#)
110. Mezzanotte, V.; Anzano, M.; Collina, E.; Marazzi, F.A.; Lasagni, M. Distribution and removal of polycyclic aromatic hydrocarbons in two Italian municipal wastewater treatment plants in 2011–2013. *Polycycl. Aromat. Compd.* **2016**, *36*, 213–228. [\[CrossRef\]](#)
111. Singh, S.; Haritash, A. Polycyclic aromatic hydrocarbons: Soil pollution and remediation. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 6489–6512.